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This article describes the Airborne Laser Experiment (ABLEX) project. ABLEX consisted of a set of experiments conducted in December 1992 and January 1993 in which a laser beam was propagated between two aircraft flying at high altitude. In these experiments scintillation patterns resulting from propagation through turbulence were recorded. The purpose of the experiments was to determine the fundamental performance limits of an adaptive optics system which performed phase only compensation as part of an Airborne Laser (ABL) theater missile defense weapon platform. Rather than field a highly complex, and expensive, airborne test-bed equipped with a state-of-the-art adaptive optics system, the physics-limited performance was determined by a novel, and quite simple method. This technique permitted a Strehl determination through measurements of the scintillation patterns resulting from propagation through turbulence. ABLEX was a scaled experiment: the aperture, operating wavelength, range to target, and platform altitude were all chosen such that the optical effects experienced by the propagating laser beam would be identical to those experienced by a high energy laser (HEL) beam. ABLEX was conducted as part of the ABL Risk Reduction program that was carried out in the first phase of the ABL program.

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HIGH ALTITUDE LASER PROPAGATION EXPERIMENT

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ABSTRACT

This article describes the Airborne Laser Experiment (ABLEX) project. ABLEX consisted of a set of experiments conducted in December, 1992 and January, 1993 in which a laser beam was propagated between two aircraft flying at high altitude. In these experiments, scintillation patterns resulting from propagation through turbulence were recorded. The purpose of the experiments was to determine the fundamental performance limits of an adaptive optics system which performed phase only compensation as part of an Airborne Laser (ABL) theater missile defense weapon platform. Rather than field a highly complex, and expensive, airborne test-bed equipped with a state-of-the art adaptive optics system, the physics-limited performance was determined by a novel, and quite simple, method. This technique permitted a Strehl determination through measurements of the scintillation patterns resulting from propagation through turbulence. ABLEX was a scaled experiment: the aperture, operating wavelength, range to target, and platform altitude were all chosen such that the optical effects experienced by the propagating laser beam would be identical to those experienced by a high energy laser (HEL) beam. ABLEX was conducted as part of the ABL Risk Reduction program that was carried out in the first phase of the ABL program.

INTRODUCTION

To explain the goals of the ABLEX effort, it is useful to first review adaptive optics systems which are used to compensate for the deleterious effects of atmospheric turbulence on laser beam propagation. The phrase "atmospheric turbulence" is used to denote the random fluctuations of the index of refraction due to small scale temperature variations in the earth's atmosphere. These refractive index fluctuations impart phase aberrations on a laser beam propagating through the atmosphere, and these phase aberrations, through the process of diffraction, change

the amplitude of the beam as well as cause beam wander and beam breakup. If the beam is from an HEL used as a weapon, turbulence can severely reduce the average intensity of the beam at the target aimpoint and vitiate the weapon's effectiveness. Even though the strength of the turbulence at the high altitudes at which an ABL would operate is much weaker than at lower altitudes, the long propagation paths in some ABL engagement scenarios suggest that the integrated effects will be significant.

To meet ABL mission requirements for engagements which include long, near horizontal propagation paths, adaptive optics systems to compensate for atmospheric turbulence will be required. The efficacy of these systems has been demonstrated for imaging applications and for ground-based laser (GBL) systems. These adaptive optics systems include some form of wavefront sensor to measure the phase aberrations due to the turbulent atmosphere and a deformable mirror (DM) to adjust the phase of either the received light in an imaging application or of the transmitted beam in a laser transmitting system.

A schematic of an adaptive optics system used to compensate an image is shown in Figure 1. For the system depicted, light from the object is split at the receiver with
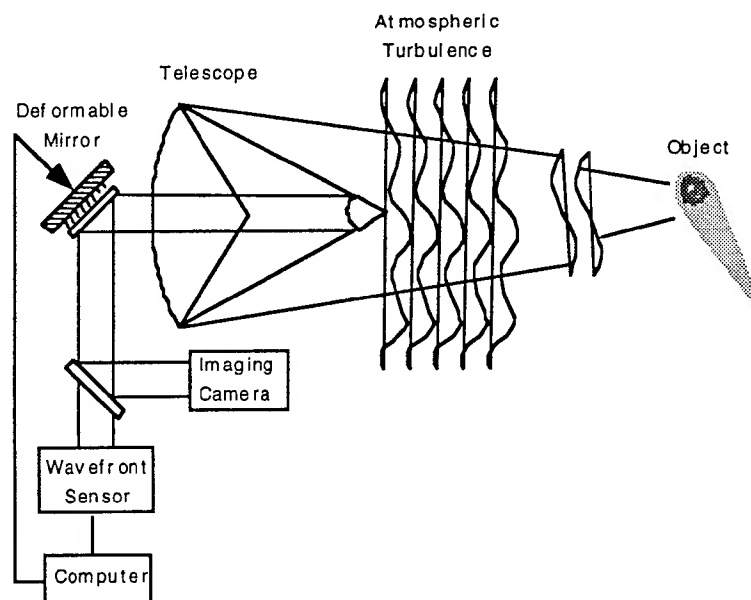

Figure 1. Schematic of an adaptive optics system used to improve the resolution of a ground-based imaging system.

part of the light sent to the camera which records the image and the rest directed to a wavefront sensor which is used to measure the phase aberrations caused by the turbulent atmosphere. The signals from the wavefront sensor are sent to a computer which calculates the appropriate commands to give to the mirror actuators to compensate the measured phase distortions. With this type of adaptive optics system, the resolution of a ground-based optical telescope can be increased by an order of magnitude or more.

One feature of ground-based systems that makes adaptive optics particularly attractive is that for those systems, turbulence manifests itself almost entirely as a phase aberration. Because turbulence in the atmosphere is much stronger at low altitudes than at high altitudes, the dominant effects are due to the atmosphere located within a few kilometers of the earth's surface. For typical ground-based systems operating in the visible or near infrared with telescopes of the meter class, virtually the entire atmosphere lies within the near field of the system. Hence, light arriving at the telescope will be severely phase aberrated, but the amplitude of the light will be very nearly uniform. Thus, if the adaptive optics system does a good job of correcting the phase, the resulting performance will be near the diffraction limit of the system.

This circumstance is in marked contrast to that which will prevail for an ABL system. For some ABL engagement scenarios of interest, the HEL beam must traverse hundreds of kilometers through the atmosphere at near horizontal elevation angles. For these scenarios, the turbulence is expected to be more or less uniformly distributed along the entire path. Light from the target, which will be used as a reference for the wavefront sensor, will arrive at the ABL strongly amplitude modulated, i.e., the light will be heavily scintillated. It was the adaptive optics performance limit due to this turbulence-induced scintillation on the reference source that ABLEX was designed to determine.

In an HEL weapon system, the ideal reference source for an adaptive optics wavefront sensor would be a point source located at the aimpoint, at least for a system which operates against a stationary target. For a moving target, such as the ABL is intended to negate, the target will move during the time it takes the reference wave to propagate to the HEL transmitter and while the HEL beam is propagating back to the target. The amount the target moves during this round trip

transit time is sometimes called the lead distance. The ideal beacon for a moving target application is a point source located one lead distance in front of the aimpoint.

It can be shown that if the amplitude profile of the transmitted HEL beam can be made to instantaneously match the amplitude profile of an ideal beacon and if the phase of the transmitted beam is controlled to equal the negative of the phase of the beacon, then the Strehl ratio of the HEL will, on average, be unity. Existing adaptive optics systems, however, compensate only the phase of the transmitted beam; they do not adjust the amplitude. Therefore, even if the phase compensation is done perfectly, the average Strehl will be less than unity. This limitation on the performance of phase only adaptive optics systems is fundamental. The ideal phase correction is the same whether or not the amplitude is compensated. If the system does not perform any sort of amplitude correction, there is no strategy which can be used to partially recover the performance lost due to the scintillation of the beacon reference. This scintillation limit is inherent to any system which does only phase compensation. It is not a function of equipment limitations such as finite signal-to-noise ratio, finite bandwidth, or a limited number of DM actuators.

The basic insight which motivated the ABLEX project is that the performance of an ideal phase only compensation system, that is, one which is limited only by the lack of a capability to perform amplitude compensation, can be determined by measuring the irradiance pattern from a point source beacon which propagates through turbulence along a representative path.

BASIC THEORY

The fundamental principle upon which ABLEX rests is the "extended Huygens-Fresnel principle" which applies to propagation through a refractive medium (Ref. 1). The principle is based on a Green's function solution to the wave equation applied to propagation in an inhomogeneous medium. The theorem can be derived by mimicking the usual development of the Fresnel integral solution to the wave equation for vacuum propagation.

It is well known that propagation through the atmosphere has a negligible effect on polarization. Therefore, the scalar wave equation is normally used to model atmospheric propagation, since it applies to each scalar component of the electric field,

and the atmosphere does not couple those components. In a refractive medium with index of refraction given by $n(\mathbf{r})$, the scalar wave equation for propagation of monochromatic radiation is

$$\left(\nabla^2 + k^2 n^2\right)U(\mathbf{r}) = 0 \tag{1}$$

where $k = 2\pi/\lambda$, and λ denotes the wavelength of the radiation.

Assume the turbulent medium resides inside a volume V, bounded by a closed surface S which contains the transmitting aperture (Fig. 2). If $\mathbf{P}$ is a point in V, let $G(\mathbf{r},\mathbf{P})$ denote the field at the point $\mathbf{r}$ produced by a point source at $\mathbf{P}$.
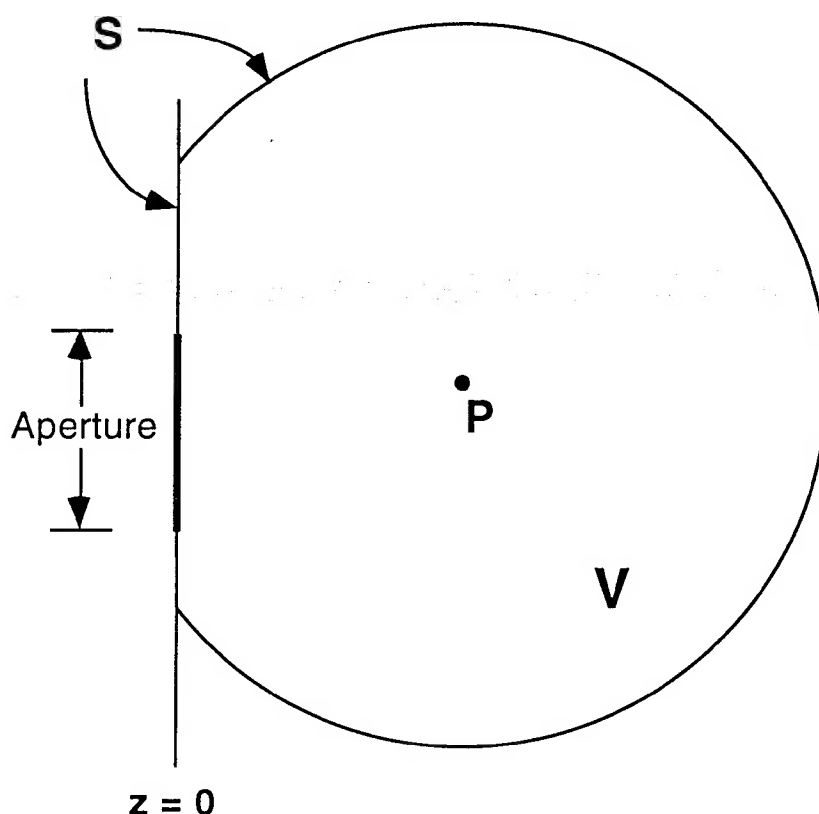

Figure 2. Geometry used in the development of the extended Huygens-Fresnel principle.

With appropriate normalization, G satisfies the equation

$$\left(\nabla^2 + k^2 n^2\right)G(\mathbf{r},\mathbf{P}) = -4\pi\delta(|\mathbf{r} - \mathbf{P}|) \tag{2}$$

If Equation 1 is multiplied by G and Equation 2 multiplied by U, then after subtraction and integration over the volume V, application of Green's theorem yields

$$U(\mathbf{P}) = \frac{1}{4\pi} \int_S (U\nabla G - G\nabla U) \cdot d\mathbf{A} \tag{3}$$

where $d\mathbf{A}$ is a surface element with normal directed into V. If the volume V is expanded to infinity and the Sommerfeld radiation condition invoked, then it can be shown that the surface integral in Equation 3 can be reduced to an integral over the transmitting aperture.

In Reference 1, arguments which parallel the development for the vacuum propagation theory are used to show that for the point **P** near the z axis, which is taken to be the optic axis of the aperture, the field U is given by

$$U(\mathbf{P}) = \frac{-i}{\lambda} \int_A U(\mathbf{r})G(\mathbf{r},\mathbf{P})d^2\mathbf{r} \tag{4}$$

where A denotes the transmitting aperture.

The function G can be written in terms of an amplitude and a phase, i.e.,

$$G(\mathbf{r},\mathbf{P}) = A_G(\mathbf{r},\mathbf{P})\exp\{i\phi_G(\mathbf{r},\mathbf{P})\} \tag{5}$$

Similarly, if the transmitted wave is expressed in terms of its amplitude and phase, then

$$U(\mathbf{r}) = A_T(\mathbf{r})\exp\{i\phi_T(\mathbf{r})\} \tag{6}$$

Using these forms for U and G in Equation 4,

$$U(\mathbf{P}) = \frac{-i}{\lambda} \int_A A_T(\mathbf{r})A_G(\mathbf{r},\mathbf{P})\exp\{i\phi_T(\mathbf{r})+i\phi_G(\mathbf{r},\mathbf{P})\} d^2\mathbf{r} \tag{7}$$

Since the amplitudes of the transmitted beam and the Green's function are always non-negative, it is observed from Equation 7 that the magnitude of the field, and hence the irradiance, at the point **P** will be maximized when

$$\phi_T(\mathbf{r}) = -\phi_G(\mathbf{r}, \mathbf{P}) \tag{8}$$

A perfect phase only compensation system would have exactly the same effect for the case in which **P** is the target aimpoint.

In ABLEX, the beacon laser which was propagated from the source aircraft to the receiver aircraft looked essentially like a point source at the receiver. Thus, within an unknown scale factor, the beacon signal was the same as the function G(**r**,**P**). The absolute strength of the beacon was unknown because of the atmospheric absorption, pointing fluctuations, power fluctuations in the laser, etc. The unknown scale factor can be normalized out, however, if, instead of trying to infer far field peak irradiance, the average Strehl ratio is computed from the data.

For the case of perfect phase compensation,

$$U(\mathbf{P}) = \frac{-i}{\lambda} \int_A A_T(\mathbf{r}) A_G(\mathbf{r}, \mathbf{P}) d^2\mathbf{r} \tag{9}$$

and

$$
\begin{aligned}
I(\mathbf{P}) &= U(\mathbf{P}) \times U^*(\mathbf{P}) \\
&= \frac{1}{\lambda^2} \iint_A A_T(\mathbf{r}_1) A_T(\mathbf{r}_2) A_G(\mathbf{r}_1, \mathbf{P}) A_G(\mathbf{r}_2, \mathbf{P}) d^2\mathbf{r}_1 d^2\mathbf{r}_2
\end{aligned}
\tag{10}
$$

The random effects of the atmospheric turbulence are entirely included in the Green's function. Taking an ensemble average (denoted by < . . . >) over all realizations of the turbulence in Equation 10 yields

$$\langle I(\mathbf{P}) \rangle = \frac{1}{\lambda^2} \iint_A A_T(\mathbf{r}_1) A_T(\mathbf{r}_2) \langle A_G(\mathbf{r}_1, \mathbf{P}) A_G(\mathbf{r}_2, \mathbf{P}) \rangle d^2\mathbf{r}_1 d^2\mathbf{r}_2 \tag{11}$$

Thus, it is seen that the average irradiance at the point P, given an ideal phase compensation system designed to maximize the intensity at P, depends on the correlation function of the amplitude of a point source propagated through the turbulence from P to the aperture. If the correlation length is large, i.e., many times the size of the aperture, then the amplitude will be essentially constant over the aperture. In this case

$$A_G(r_1, P) = A_G(r_2, P) \tag{12}$$

and

$$\langle A_G(r_1, P) A_G(r_2, P) \rangle = \langle A_G^2 \rangle \tag{13}$$

Only the random real index of refraction fluctuations in the atmosphere are of interest. Since these do not preferentially scatter light either into or out of the aperture, the right-hand side of Equation 13 will have the same value that it would have in the case of vacuum propagation. In this case, the average irradiance at P will be the same as for vacuum propagation, i.e., the average Strehl ratio will be unity.

Note that the Strehl ratio can be written as

$$I_{rel} = \frac{\frac{1}{\lambda^2} \iint\limits_A A_T(r_1) A_T(r_2) \langle A_G(r_1, P) A_G(r_2, P) \rangle d^2 r_1 d^2 r_2}{\frac{1}{\lambda^2} \iint\limits_A A_T(r_1) A_T(r_2) \langle A_G^2 \rangle d^2 r_1 d^2 r_2} \tag{14}$$

In ABLEX, the laser produced a beacon amplitude A_B at the aperture on ARGUS which was proportional, via an unknown scale factor, to the Green's function, which must satisfy Equation 2.

$$A_G(r_1, P) = K A_B(r_1) \tag{15}$$

Inserting this expression into Equation 15 yields an expression for I_{rel} in terms of the measured beacon.

$$I_{rel} = \frac{\iint_A A_T(\mathbf{r_1})A_T(\mathbf{r_2})\langle A_B(\mathbf{r_1})A_B(\mathbf{r_2})\rangle d^2\mathbf{r_1}d^2\mathbf{r_2}}{\iint_A A_T(\mathbf{r_1})A_T(\mathbf{r_2})\langle A_B^2\rangle d^2\mathbf{r_1}d^2\mathbf{r_2}} \tag{16}$$

The factor K cancels out in the above expression since it has been assumed to be independent of the random turbulence.

It is perhaps useful to use Equation 16 to illustrate the role of the amplitude correlation function in determining the average Strehl ratio. As previously noted in the case for which the amplitude is perfectly correlated over the aperture, i.e., the amplitude is constant over the aperture, the average Strehl ratio is unity. At the other extreme, the amplitude correlation length is zero. In this case, the amplitude at one point is uncorrelated with the amplitude at any other point, i.e.,

$$\langle A_G(\mathbf{r_1},\mathbf{P})A_G(\mathbf{r_2},\mathbf{P})\rangle = \langle A_G(\mathbf{r_1},\mathbf{P})\rangle\langle A_G(\mathbf{r_2},\mathbf{P})\rangle \tag{17}$$

It is not obvious what Strehl this yields in general, but in the case that the amplitude is log-normal, the situation that applies in the weak turbulence limit, it can be shown that conservation of energy dictates that the mean and variance of the log-amplitude satisfy the relation

$$\langle \chi \rangle = -\sigma_\chi^2 \tag{18}$$

In this case, it is straightforward to show that

$$I_{rel} = \exp\{-\sigma_\chi^2\} \tag{19}$$

This comment is not intended to suggest that the statistics are really log-normal in the strong scintillation limit where the correlation length might be expected to be very short. It is included only to demonstrate that the correlation length is an important parameter for determining I_{rel}.

In the above analysis, for generality, the amplitude of the transmitted beam has been retained in the expressions for the Strehl and for the average far-field irradiance profile. In the reduction of the ABLEX data, these quantities were calculated only for

a uniform amplitude beam, i.e., $A_T(r)$ equal to a constant. In this case, the Strehl is given by

$$
\begin{aligned}
I_{rel} &= \frac{\iint\limits_{A} \langle A_B(\mathbf{r}_1) A_B(\mathbf{r}_2) \rangle d^2\mathbf{r}_1 d^2\mathbf{r}_2}{\iint\limits_{A} \langle A_B^2 \rangle d^2\mathbf{r}_1 d^2\mathbf{r}_2} \\
&= \frac{1}{A^2 \langle A_B^2 \rangle} \iint\limits_{A} \langle A_B(\mathbf{r}_1) A_B(\mathbf{r}_2) \rangle d^2\mathbf{r}_1 d^2\mathbf{r}_2
\end{aligned}
\tag{20}
$$

where A denotes the area of the ABLEX receiving aperture. Equation 20 was applied to the ABLEX data instead of the more general Equation 16.

EXPERIMENT DESCRIPTION

The ABLEX experiment was conducted using two aircraft, a source aircraft, HARP, and a receiver aircraft known as ARGUS. HARP is a Lear 36A operated by the Aeromet Corporation, Tulsa, Oklahoma. ARGUS is an Air Force NC -135E operated by the Phillips Laboratory Flight Test Branch.

The principle hardware subsystems for ABLEX are laser, laser pointing system, receiver telescope and gimbal, science sensor, and receiver pointing system. Additionally, each aircraft had a laser diode beacon that served as track sources for the laser and receiver pointing systems. Figure 3 depicts the main elements of the HARP transmitter while Figure 4 depicts the main elements of the ABLEX receiver.

A divergent laser beam, exiting the aircraft at 1-2 cm in diameter, was projected through atmospheric turbulence onto an 85-cm diameter receiver on ARGUS. The beam, several hundred meters in diameter at ARGUS, behaved essentially like a point source. ARGUS included an optical system (Fig. 5) that imaged the scintillation pattern onto a focal plane array. This scintillation pattern was recorded and used to compute the scintillation limit on ABL adaptive optics performance.
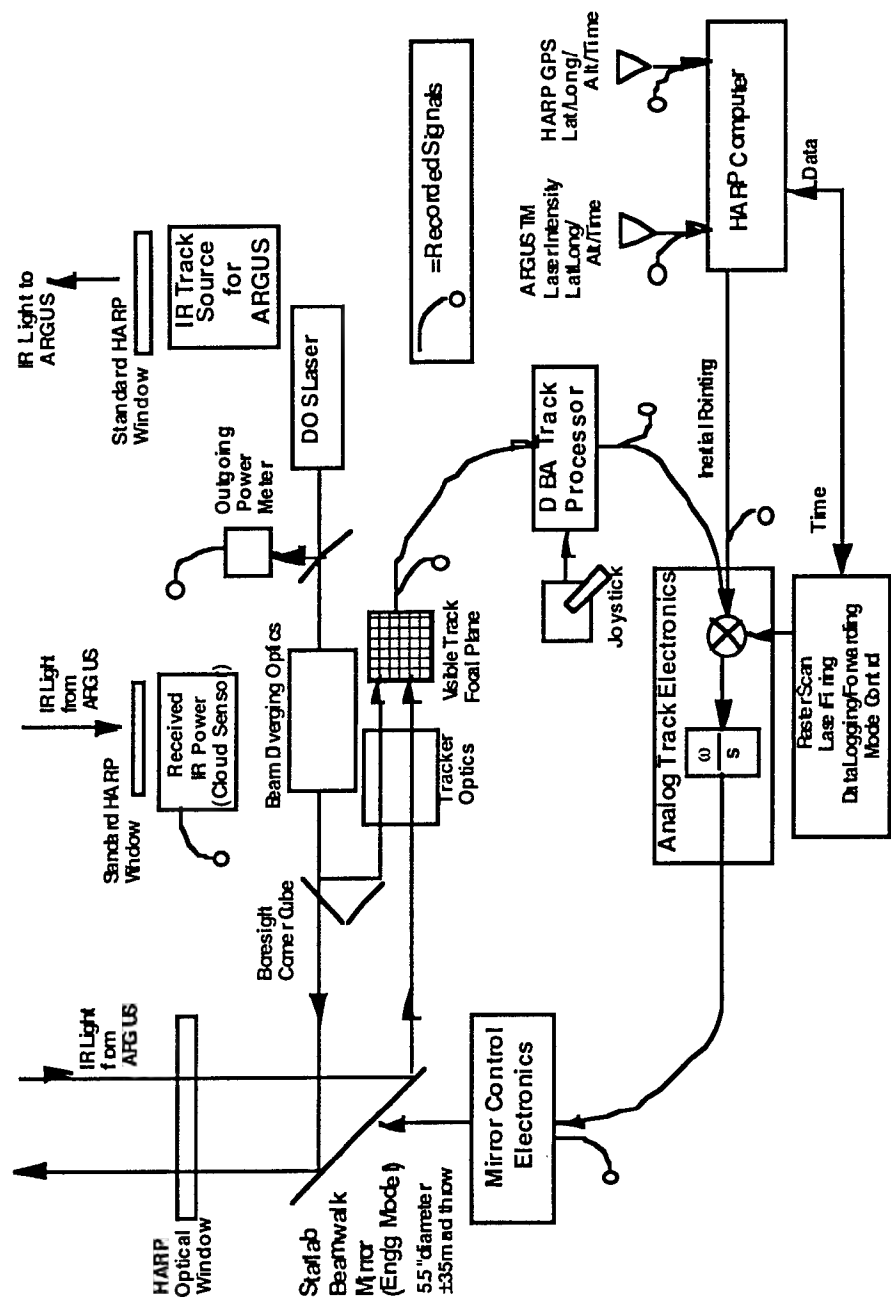
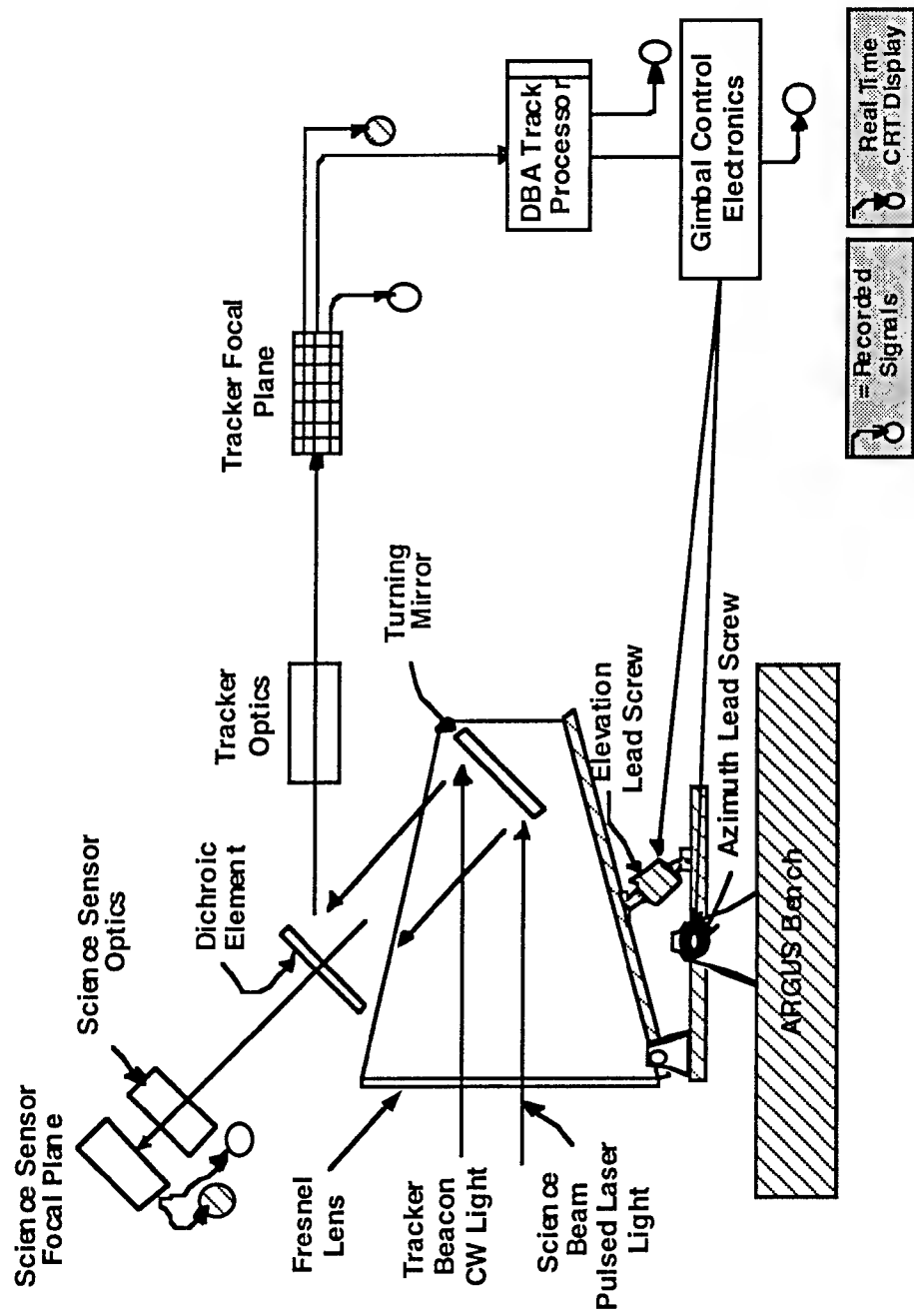Figure 3. HARP functional block diagram.
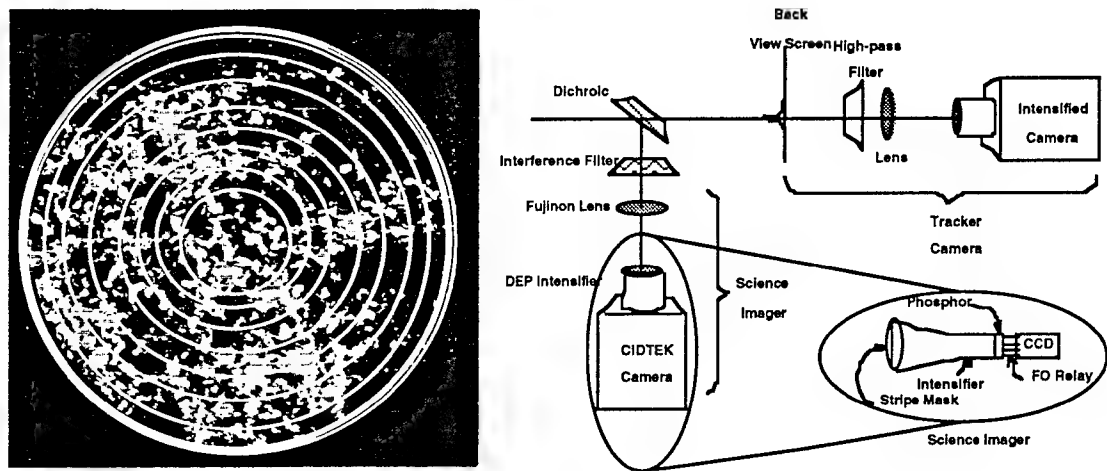
Figure 4. ARGUS receiver concept.

Figure 5. Science camera and tracking sensor.

One particular unique feature of the ABLEX experiment was the large aperture optical system. The focal plane camera formed an image of the irradiance pattern at the aperture of the optical system, not an image of the source. Thus, the 80-cm collector served only as a condensing element, not an imaging forming element. Also, the window was not a part of the image forming system.

Consequently, the optical quality of these elements did not have to be high since these elements were not part of the imaging forming system. The window was Plexiglas and a plastic Fresnel lens was used as the condensing element. The large aberrations in these low quality optics did not affect the image quality of the science sensor although the tracking camera was affected. The camera lens which imaged the irradiance pattern and the dichroic beam splitter, which diverted the beacon light into a tracking sensor, were the only elements requiring good optical quality.

In ABLEX, the laser beam transmitted from HARP can be thought of as a surrogate for the adaptive optics beacon originating at the target. The ARGUS aircraft can be viewed as a substitute for the ABL platform with the receiving aperture serving as a surrogate for the ABL transmitter.

The parameters chosen for the ABLEX tests were not identical to those which are anticipated for an ABL system but, rather, were chosen to be scaled to an ABL system and engagement scenario. At the time ABLEX was conceived, there was no design for an ABL system, but it is thought that an ABL will operate with an HEL wavelength between 1.0 and 3.8 μm with a transmitting aperture diameter between 1.5 and 2.0 m.

Since it was not feasible within the ABLEX schedule and funding constraints to incorporate such a large aperture on an airborne platform, experiment parameters were chosen which used a smaller aperture but gave the same value for the scintillation Strehl limit. Dr. David Fried of the Optical Sciences Company, Anaheim, California developed scaling relationships, based on the assumption of Kolmogorov turbulence, which ensured that two systems operating with different wavelengths, aperture diameters, propagation distances, and turbulence strengths would give identical results for the scintillation Strehl limit provided they satisfied the scaling relations. Based on Dr. Fried's analysis, ABLEX was designed with an 85-cm receiving aperture and used a 0.53-μm laser as a surrogate for an ideal point source beacon. The experiments included tests with 200-km propagation paths. With these experiment parameters, the ABLEX tests were scaled to an ABL system operating at 1.3-μm (corresponding to a chemical oxygen-iodine laser or COIL, one of the leading candidate laser systems), a transmitter diameter of 2.0 m, and a propagation path of 400 km.

OPERATIONS

There was a total of 10 ABLEX missions. One mission was flown in New Mexico across the White Sands Missile Range (WSMR) in December, 1992 and another in January, 1993. After the second WSMR mission, eight missions were flown in central Montana during January.

The purpose of the WSMR missions was two-fold: First was the evaluation of hardware performance and systems checkout. The initial flight tests provided the first opportunity to simultaneously test and evaluate all systems at once. Second, they were training missions.

The mainline ABLEX missions were flown in Montana. There were two reasons for moving the operations there: (1) At WSMR, the laser could only be operated within the range itself. Because of the narrow width of the range, the firing time was limited to 10 min. (2) The requirement to fly above the tropopause dictated that the mission be flown in the more northern latitudes where the tropopause height is lower. Fairchild Air Force Base, near Spokane in eastern Washington state was selected for the staging area.

The missions were conducted within airspace bounded between 46 and 49 deg North Latitude and between 107 and 117 deg West Longitude. The Salt Lake Center FAA set up a moving Altitude Reservation (ALTRV) for laser safety. The ALTRV extended 10 nmi to the right, 3 nmi in front and back, and 5000 ft below and above HARP. No other aircraft was permitted to fly co-altitude with HARP. HARP was to fly a consistent racetrack pattern within the designated airspace so that the moving ALTRV could be readily maintained by the FAA.

All ABLEX missions were flown at night between the hours of 2300 and 0400. Although daytime operations are more restrictive due to the volume of air traffic, the primary reason for night operations was the inability to perform the scintillation measurements during daytime. This was due to the wide field-of-view of the Fresnel lens which precluded the use of a field stop for background radiation reduction. Also, the track source, because it was diverged 10 deg, was not bright enough to provide sufficient discrimination against background radiation.

In addition to flying the two aircraft at ranges which would satisfy scaling requirements, it was desired to obtain data at a variety of ranges and altitudes, and above, below, and through the tropopause, if possible. Figure 6 shows the parameter space covered. The hatched area represents the variation in the height of the tropopause. The lines through the tropopause band do not necessarily represent a measurement through the tropopause. As it turned out, measurements below and through the tropopause were limited because of the cloud layers that were almost always present at the lower altitudes during the month of January.
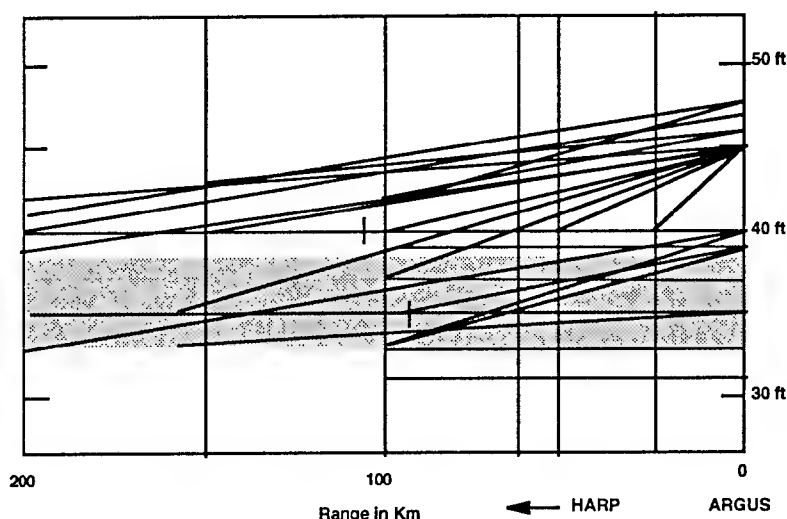
Figure 6. ABLEX Parameter Space. (The vertical axis represents altitude. ARGUS is at the right end of a line and HARP is at the left end. The hatched region indicates the variation in tropopause height.)

The scintillation measurements were supplemented by turbulence measurements. Balloons carrying thermosonde packages were launched from Malstrom Air Force Base in Montana shortly prior to the ABLEX flights. These data provided C_n^2 vertical profiles. Fast response temperature probes on ARGUS provided data on the horizontal distribution of turbulence.

RESULTS

A detailed summary of the ABLEX results does not appear here. The results will be published in a Final Report. What is presented here is a condensation of those results.

The Strehl ratios that were observed fell within the range predicted on the basis of the CLEAR 1 atmospheric model. The Strehl ratios reported here are the scintillation-limited Strehls, i.e., the Strehls that could be attained with idealized adaptive optics systems. Critical engineering factors such as sensor signal-to-noise ratio, fitting errors, bandwidth, tracking, and nature of the beacon source were not taken into account.

A historically popular notion is that, in the absence of adverse weather conditions, the upper atmosphere is relatively stable (from an optical turbulence point of view) at high altitude. The results of ABLEX indicate otherwise.

The atmosphere is highly variable. The scintillation patterns that were observed vary from the highly unusual salt-and-pepper patterns illustrated in Figure 7 to patterns with very large speckle blobs illustrated in Figure 8 (the horizontal stripes are artifacts due to printing). Then there is the entire range between. This variability seemed to be independent of altitude and/or range. The patterns could persist for long periods of time, 20-30 min, but could change from one extreme to the other in a minute (sometimes seconds) or less. Or the change could be more gradual.

Then there was the unexpected, as illustrated in Figure 9. These fringe-like patterns were frequently observed but occurred only a small percentage of the time. Whatever produced them, although atmospherically related, turbulence theory does not account for them.

Figure 10 is a plot of the "temporal" Strehl for a typical data sequence. The average Strehl for this sequence is 81 percent. It is high because the low Strehls have been compensated by very high Strehls. The excursions above unity are due to the occasional lens-like behavior of the atmosphere and are not unexpected.
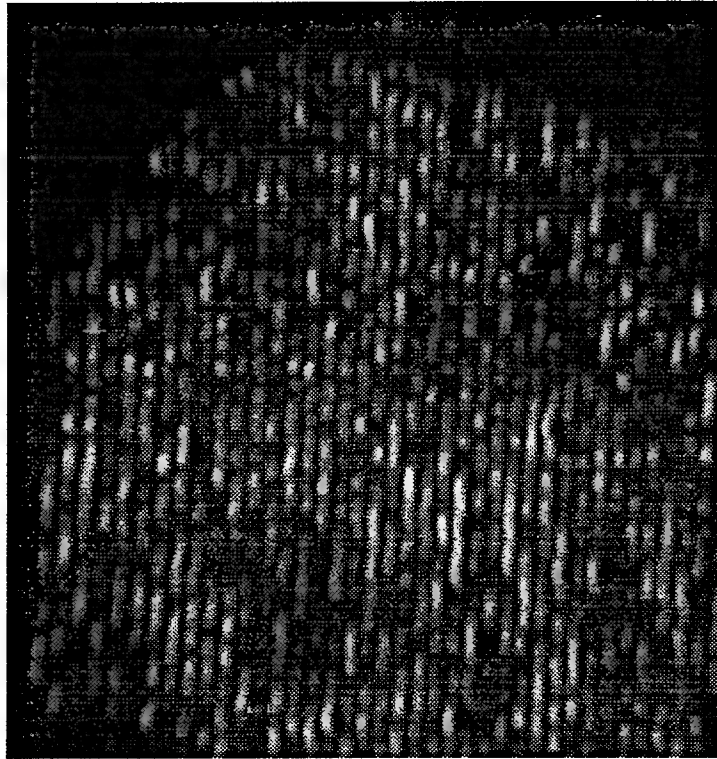
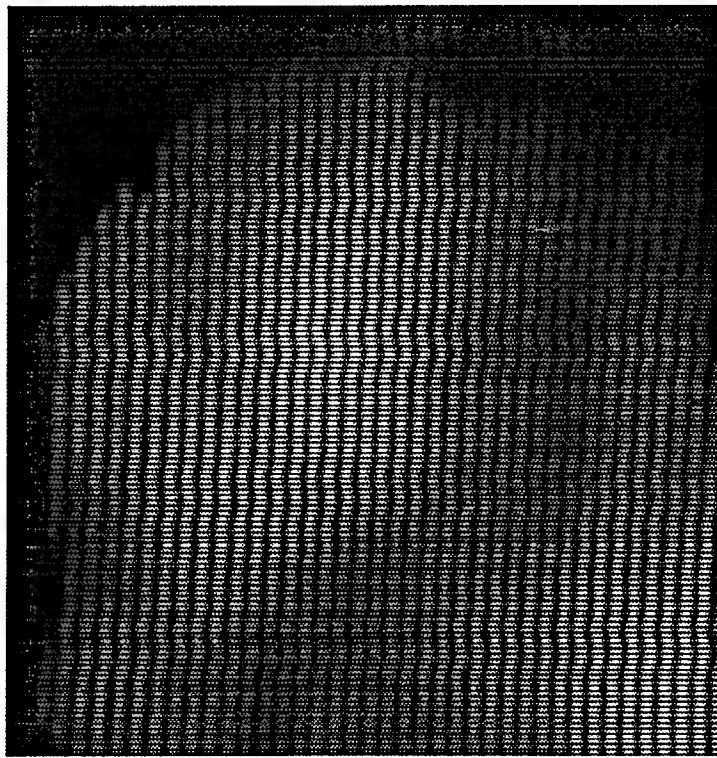Figure 7. Salt and pepper scintillation pattern.

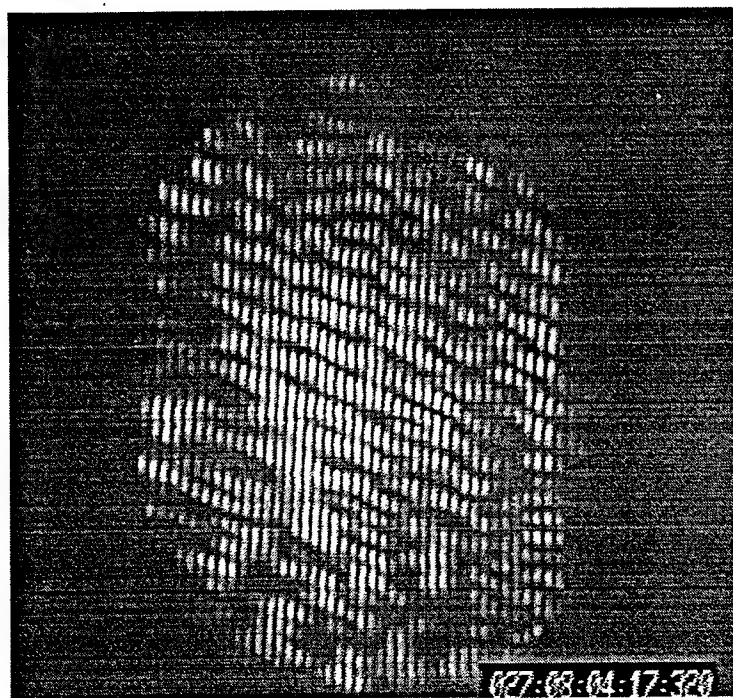

Figure 8. Large scale scintillation pattern.
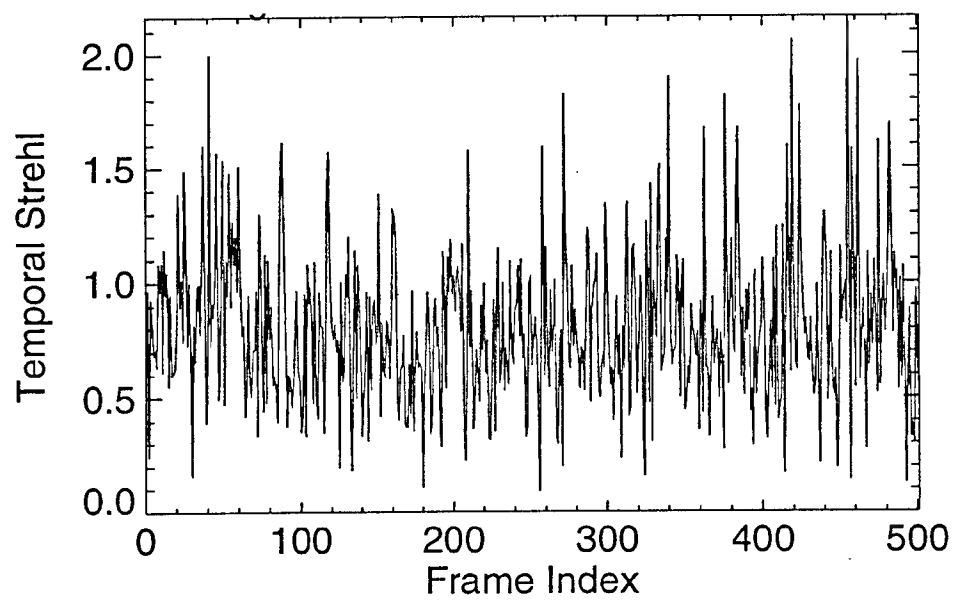
Figure 9. Fringe-like pattern.

Figure 10. Temporal Strehl ratio.

Fried and Roberts (Ref. 2) predicted this behavior, which they refer to as beacon coupling. Large Strehls are observed whenever there is strong coupling of the beacon light into the transmitter's receiver aperture and just the opposite whenever the coupling is low. Figure 11 presents the results of a simulation showing how the Strehl ratio is highly correlated to the amount of beacon light coupled into the aperture. This behavior was observed in ABLEX (Fig. 12).

Figures 13 and 14 are composite histograms of all the 100 and 200-km Strehl data gathered in the Montana missions. These histograms were generated without regard to altitude. No clear range dependence is indicated in these histograms, although that dependence could be hidden due to the fact that most of the 200-km data were taken at higher altitude. However grouped, these histograms clearly show that the scintillation limited Strehl is at an acceptable level.

The ABLEX sensor was able to provide more than just Strehl data. This pupil plane sensor also yields scintillation statistics. The amplitude correlation length, which plays a vital role in determining the average Strehl ratio, as well as the log-amplitude variance of the scintillation could also be determined. Figures 15 and 16 are distributions for the log amplitude variances that were observed.

The scintillation statistics are largely log-normal distributed. The linear portion of Figure 17, which is a plot of the cumulative intensity probability distribution function observed in a typical data set, provides a graphic illustration of this behavior. The inverse of the slope of this function is the log-amplitude variance for the data set. The nonlinear behavior is thought to be due to inadequacies in the sensor and the data acquisition system.

This discussion is concluded by noting that a rich set of atmospheric data was obtained from the ABLEX experiments. These data confirmed previous notions, based on the CLEAR 1 atmospheric turbulence model, that phase-only turbulence compensation can provide sufficient performance for an ABL system operating under similar scaled conditions. The unresolved phenomenology issues (as opposed to engineering issues associated with the beacon, tracking, adaptive optics system design, etc., which were not an objective of ABLEX) are related to the variability of the atmosphere and a more robust definition of the turbulence model(s) to be used to predict ABL performance. In addition, there are the uncertain transmission characteristics of the atmosphere over the slant paths of interests.
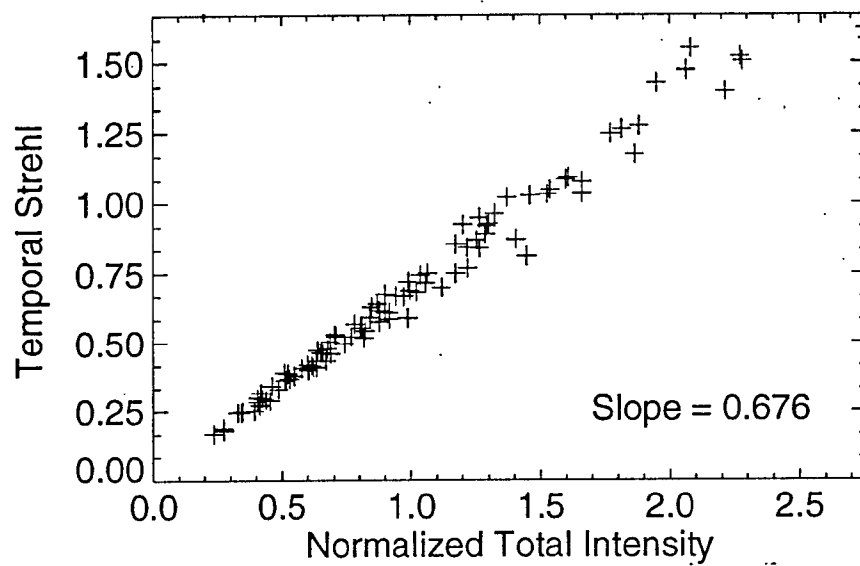
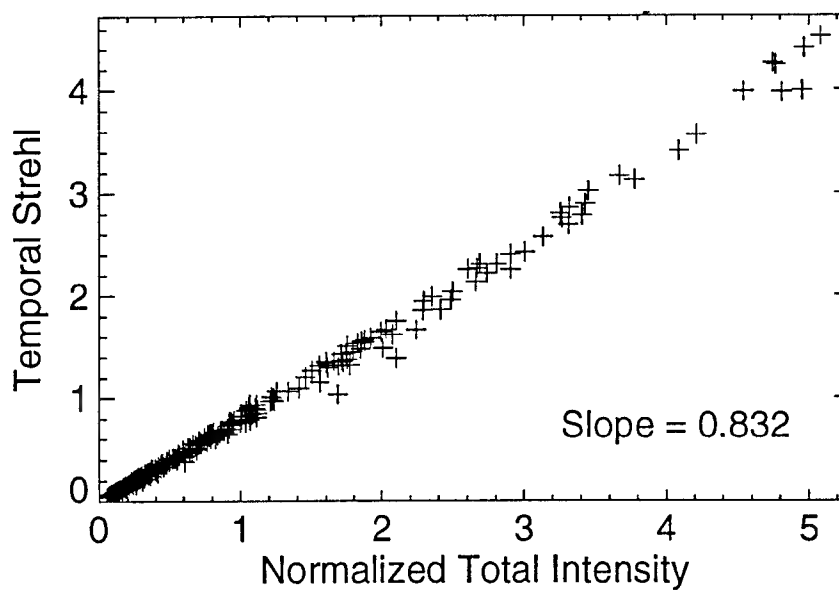Figure 11. Effect of beacon coupling on Strehl - simulation results.

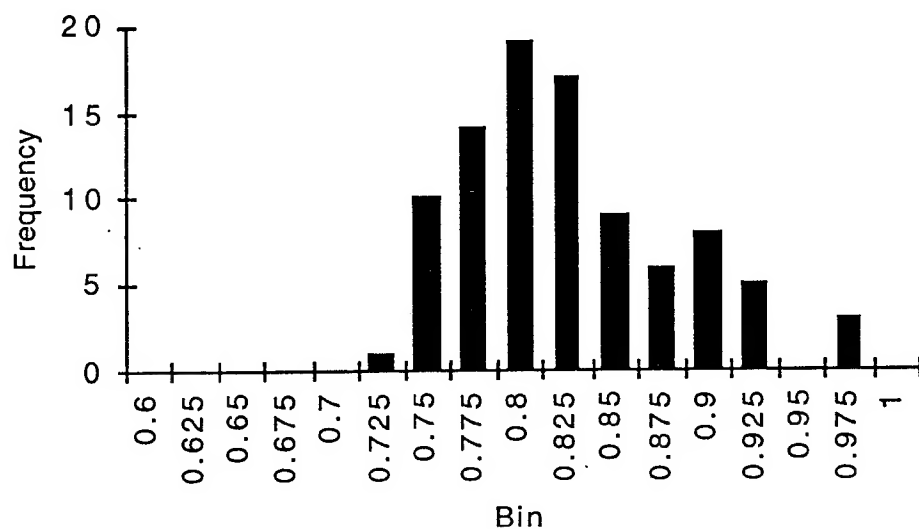Figure 12 Effect of beacon coupling on Strehl - ABLEX results.

Figure 13. Distribution of Strehls for all 100-km data sets.
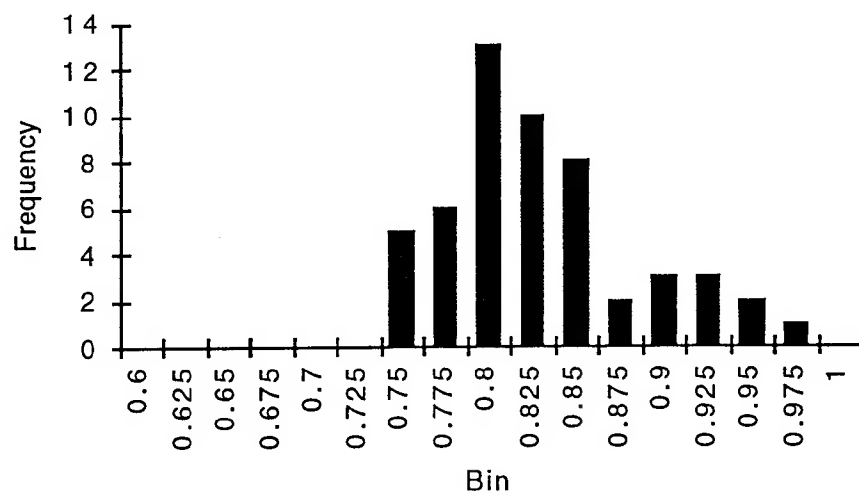(Mean = 0.8383, Standard Deviation = 0.0562)

Figure 14. Distribution of Strehls for all 200-km data sets.
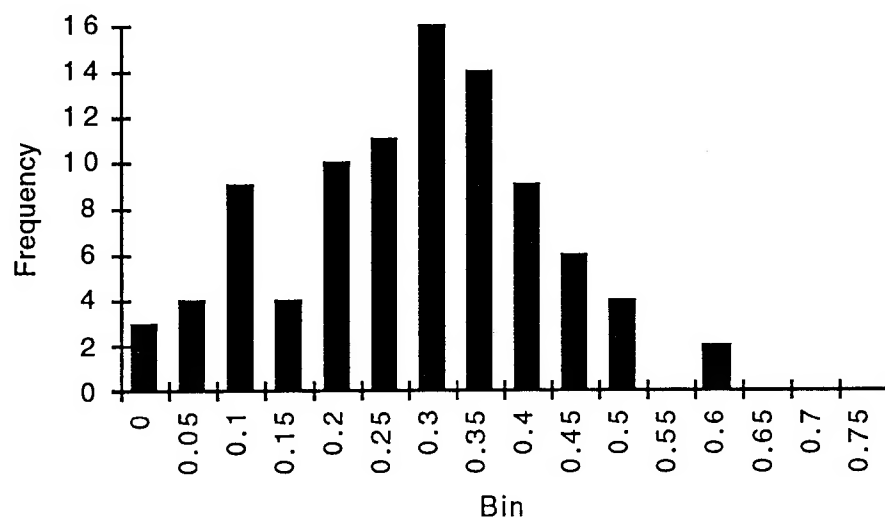(Mean = 0.8423, Standard Deviation = 0.0548)

Figure 15. Distribution of log amplitude variances for all 100-km data sets.
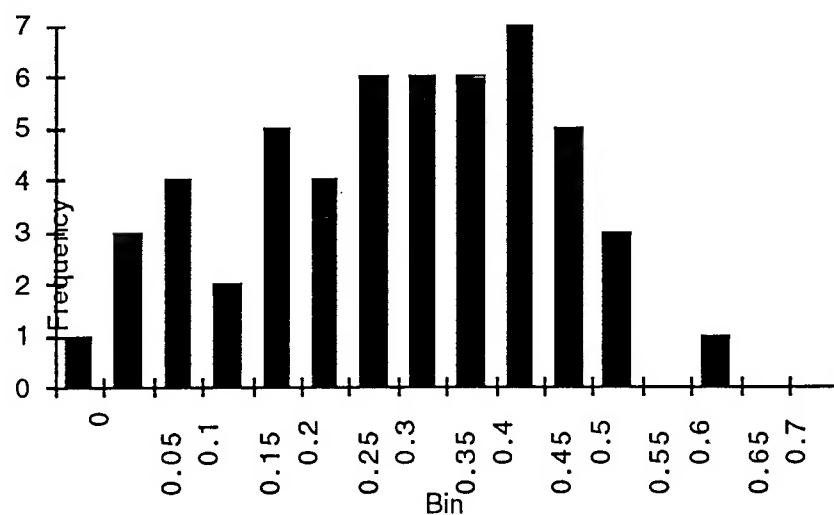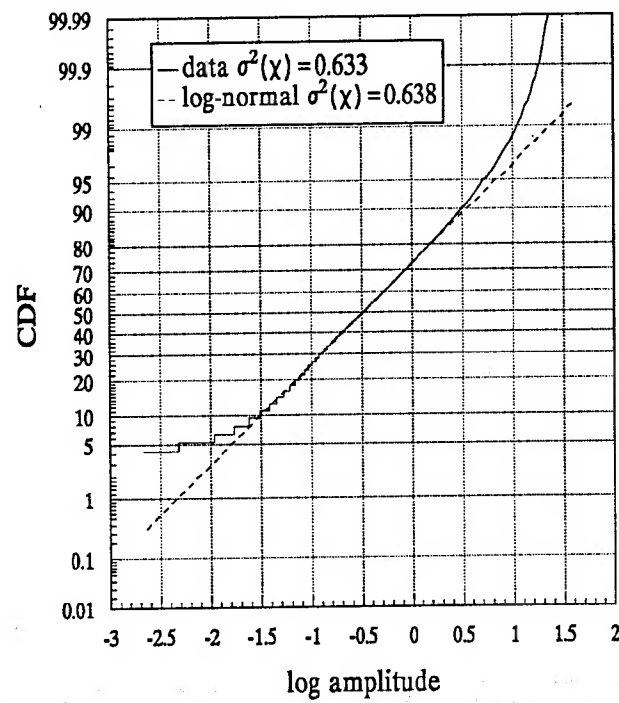(Mean = 0.3043, Standard Deviation = 0.1332).

Figure 16. Distribution of log amplitude variances for all 200-km data sets.
(Mean = 0.3468, Standard Deviation = 0.1542).

Figure 17. Cumulative log amplitude probability distribution function.

ACKNOWLEDGMENTS

REFERENCES

1. Lutormirski, R. F. and Yura, H. T. "Propagation of a Finite Optical Beam in an Inhomogeneous Medium", Applied Optics, Vol. 10, 1652-1658, 1971.

2. Fried, D. L. and Roberts, P. H. "Can Adaptive Optics Be Usefully Employed When The Scintillation is Severe?", the Optical Sciences Company, Anaheim, California, Briefing Chart BC-662, January, 1992.